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DEVELOPMENT AND IMPLEMENTATION OF A SYSTEM FOR THE PREDICTION OF FIRE-INDUCED TREE MORTALITY

Final Report of JFSP Project 00-1-1-06

Development and implementation of a system for the prediction of fire-induced tree mortality

Presented to the
Governing Board of the Joint Fire Sciences Program

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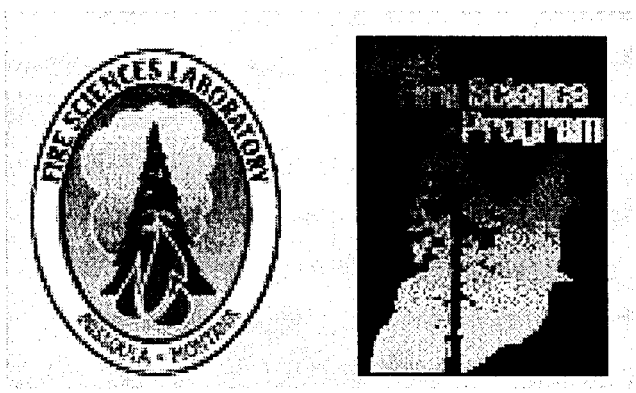

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Executive Summary

The following comprises the final report of Joint Fire Science Program project 00-1-1-06. Research efforts have resulted in the development of a stand-alone executable version of the model (***FireStem***). ***FireStem*** predicts species and diameter dependent mortality of the tree stem cambial tissue as a function of fire intensity and duration. In what appears to be a perfect match, near the start of this project, we were contacted by Dr. Matt Dickinson of the Northeastern Research Station. Matt had been working to develop an advanced model for tissue necrosis. Recognizing that our strengths lay in thermal modeling and that Dr. Dickinson's lay in mortality modeling, we worked together to include both in ***FireStem***. Thus ***FireStem*** consists of the most advanced models for thermal transport and tissue necrosis. The scientific aspects of this study have been documented through the publication of a masters degree thesis, five presentations at conferences or technical workshops, and four peer reviewed journal publications (one currently published, two in review and one nearly ready for submission) and a website: (http://www.firelab.org/fbp/fbresearch/stemheating/Homepage.htm).

An early and well respected forest researcher (Van Wagner 1973) pointed out that the basic question that must be addressed by any fire-induced tree mortality model is which trees will live or die for a given fire behavior scenario. An analysis of ***FireStem***'s accuracy in predicting fire-induced tree stem cambial mortality indicates that for the four species studied mortality is accurately predicted 75% of the time. However the real benefit will likely come as the ***FireStem*** model is directly linked to fire behavior models. This will provide a tool whereby managers can explore the mortality resulting from various prescribed fire scenarios long before actually applying fire. Something not as easily accomplished with currently available empirical models. In the author's opinion, the experimental methods and models developed as part of this research effort represent the most accurate physics-based models of fire-induced stem heating and cambial mortality developed to date.

It is our belief that this effort can form the foundation for what we hope will be an ongoing research effort to develop a computer based system for evaluating forest stand mortality due to any combination of root, stem or crown scorch and heating across a range of species and age classes. Various applications are envisioned: 1) a "gaming" mode to explore species and size specific mortality associated with specific prescribed fire scenarios prior to igniting the fire, 2) a "forensic analysis" mode to reconstruct the fire behavior that caused the current condition and 3) a "forecast" mode to estimate mortality from natural or prescribed fires that are currently burning.

What direction should future work take? Three possible options are: 1) Extend ***FireStem*** to include additional species by collecting needed thermal and physical properties and testing model predictions against experiments; 2) Modify ***FireStem*** to simulate heat transfer in small diameter stems, needles and leaves comprising the plant canopy to permit the prediction of canopy scorch and mortality; 3) Link the heat transfer model in ***FireStem*** with a model of soil heating to provide a comprehensive tool for predicting root mortality. If these additional steps are completed the resulting system of models could provide land managers with an objective tool for assessing overall post fire tree mortality due to the combined effects of root, stem and canopy heating. A prediction of tree mortality could then be based on the expected fire behavior, tree species, and size. The model could also be modified to estimate fire scar size as a function of fire intensity, fire duration, plant species and diameter, providing a tool for reconstructing past fire histories based on fire scar information.

In the following we present an overview of the research effort, challenges and results. We conclude with a summary of the status of the study and present some thoughts about related future efforts.

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Development and implementation of a system for the prediction of fire-induced tree mortality

Introduction

Frequently, a primary objective of management efforts is the survival of selected plant species and the reduction of competing species. Thus, before ignition, land managers often need to estimate the effects of prescribed fire. Methods and models that predict fire-induced tree mortality can be used by manager's as they weigh the "pros and cons" of land management options at their disposal (Martin 1963, Peterson and Ryan 1986, Hengst and Dawson 1994, Durcey *et al.* 1996). The objective of this research study was to develop a new computer based model that can be linked to fire behavior models and accurately predicts tree survival or mortality due to heating of the tree bole or stem as a function of tree species, stem diameter and fire intensity. The primary objective of this research effort was to develop a model that could be linked with fire behavior models to accurately predict fire-induced stem injury. This required the development of two separate models, one to simulate the energy transfer through the plant stem and a second to simulate the tissue necrosis that occurs as the living tissue in the tree stem are heated. ***FireStem*** is the culmination of this effort. It couples the thermal model developed in this effort (Jones *et al.* 2004a) with both Martins (1963) cambial tissue mortality model and the newly developed cellular necrosis model reported by Dickinson and Johnson (2004).

Currently land managers use personal experience and fire behavior prediction systems to estimate the expected fire intensity and duration. They then combine these tools with their knowledge of plant response to fires and empirically derived methods to deduce broad-scale estimates of fire-caused plant mortality. This approach has several drawbacks: it depends on the manager's experience level, requires site and species specific data and/or empirical models, and lacks objectivity and repeatability. This study was based on the premise that a physics-based heat transfer model of energy transfer into a plant stem could be linked to current and new fire behavior models, something not possible with currently used empirical models, and that the resulting tool would provide some advantage over currently used systems for estimating post fire tree mortality. This new tool would allow fire practitioners to evaluate the effects of competing fire-based land management options long before striking the match.

The primary differences between previous research efforts and the model developed for this project are four-fold: 1) this model includes more complete accounting of all of the energy production and absorption processes occurring when the plant stem is heated, 2) the model incorporates a spatially varying moisture profile in the stem, 3) includes a heat flux boundary condition at the exterior surface so that the model can be readily linked to fire behavior models, and 4) the energy transfer model has been linked with a sophisticated tissue necrosis model that more accurately accounts for species specific tissue response to heating and the impact of temperature magnitude and duration on tissue viability. This combined model (heat transfer plus tissue mortality) has a greater potential to accurately predict thermally-induced necrosis of the cambial tissue in plant stems than any previously reported work.

The scientific literature indicates that two issues have frustrated past efforts to link fire behavior and plant mortality models. These issues are: 1) Currently available fire models do not provide the temporally and spatially varying temperature and heat flux information needed by physics-based transient stem heating models; 2) The empirically based plant mortality models cannot be easily linked to fire model outputs such as spreadrate or fireline intensity.

A stand-alone executable version of the model (***FireStem***) has been produced that predicts species and diameter dependent mortality for a specified fire intensity and duration. For this study we concentrated on four tree species selected to generally represent two hardwood and two softwood species (*Acer rubru, Quercus prinus, Pinus ponderosa and Pseudotsuga menziesii*) of interest to forest managers in North America.

Previous Work

Two different tools are needed for a successful comprehensive fire-induced tree mortality model. One is an accurate (within acceptable bounds) method for predicting the temporal and spatial energy release from a fire as a function of fuel and environmental conditions. The other is a method for predicting the response of the plant tissues to heating. Past efforts have yielded systems like BEHAVE (Andrews 1986), NEXUS (Scott and Reinhardt 2001), and FARSITE (Finney 1998) for the prediction of fire behavior over a range of fuel and environmental conditions. Work continues to be directed at improving existing systems and developing more accurate and useful methods for predicting fire behavior (Andrews, 1998). This project is directed at the development of the second tool: a method for predicting the response of plant stems to heating.

Individual tree mortality is related to species, age, and thermal injury to the roots, stem and canopy (Martin 1965, Van Wagner 1973, Ryan 2000). Predictive models of these processes can be classified into two general categories: empirical and theoretical (physics based) models. For the purposes of this study, empirical models are defined as those based primarily on statistical correlations of experimentally measured fire behavior and tree mortality. The biological and physical processes governing the heating and subsequent plant injury are implicitly included in the correlations. Empirical models and methods most often attempt to utilize visual indicators of fire intensity such as surface fuel consumption, stem height scorch, or degree of canopy scorch to predict tree mortality. Theoretical models are primarily based on a mathematical treatment of the physical processes that govern the energy transfer through the stem, yielding a prediction of the local temperature history within the stem and the resulting local tissue response. Some empiricism is always present in the submodels comprising the theoretical model predictive system (*e.g.*, correlations for thermal conductivity). Likewise empirical models often incorporate understanding of the physical processes in the model formulation.

Empirical Methods

Early efforts focused principally on developing rules for mortality based on observed fire indicators (*e.g.*, scarring, flame height, *etc.*) Flint (1925) identified seven factors affecting tree survivability: bark thickness, resin content of bark, rooting patterns, branching patterns and stand conditions, foliage flammability, and lichen growth. Eleven Idaho species were rated with respect to these factors, and a relative degree of fire resistance was given for each. Building on Flint's work, Starker (1934) suggested that a rating scale of fire resistance was needed. McCarthy and Sims (1935) introduced an empirical method based on post-fire observations for estimating fire-induced tree mortality rates. Shirley (1936) reported

measurements of lethal temperatures for various plant tissues.

Recognizing the importance that physics-based approaches might play, others focused on measuring the thermal and physical characteristics of wood and bark required by theoretical models (Lamb and Marden 1968, Martin and Crist 1968, Spalt and Reifsnyder 1962, Kayll 1963, Martin 1963, Fahnestock and Hare 1964, Hare 1965a, Hare 1965b, McArthur 1967, Vines 1968, Gill and Ashton 1968).

In an effort to characterize the thermal environment around tree stems, Martin and Davis (1961) recorded and analyzed tree stem surface temperatures near ground level during fires. Kayll (1963) reports temperatures at the exterior surfaces and cambiums of trees exposed to heating from a propane torch as a function of species and diameter, concluding that energy transfer through the bark plates was more critical than that through the fissures from a thermal modeling aspect. Martin (1963) recorded surface temperatures for trees during low-intensity fires and proposed that mortality could be predicted by linking thermal and mortality models. Fahnestock and Hare (1964) conducted field experiments in which bark surface and cambium temperatures were measured for stems subjected to heading and backing fires. Using a propane torch as the heat source Hare (1965a, b) measured the time for the cambium to reach lethal temperatures as a function of tree stem diameter and species. In a laboratory setting Gill and Ashton (1968) applied a known heat flux to tree stems and measured the response of the surface and cambial temperatures. Vines (1968) instrumented and measured the temperature response of living trees subjected to heating. Some studies have characterized fire-induced scarring of plant stems at an intensity that is insufficient to kill the tree (Gill 1974, Tunstall *et al.* 1976, Gutsell and Johnson 1996).

Laboratory and field data have provided increased understanding of the mechanisms governing fire-induced tissue injury (*e.g.* Nelson 1952, Peterson and Arbaugh 1986, Wyant *et al.* 1986, Saveland *et al.* 1990, Harrington 1987, 1993, Hengst and Dawson 1994, Russell and Dawson 1994, Ryan 1998). The important work of Peterson and Ryan (1986) combines the understanding developed by earlier researchers with experimental observations to develop empirical correlations for predicting the probability of plant mortality due to heating. These correlations form the primary basis for systems currently used by forest managers in North America to make predictions of tree mortality based on fuel and fire descriptors (Peterson and Ryan 1986, Ryan and Reinhardt 1988, Greene and Schilling 1987).

Theoretical Methods

Theoretical methods for predicting tissue heating and its response to the resulting elevated temperatures have included both analytical and numerical modeling efforts. Mercer *et al.* (1994) and Mercer and Weber (2001) solved the one-dimensional differential heat conduction equation analytically, and based estimates of stem mortality on resulting definitions of time-to-necrosis at a range of fixed temperatures. Dickinson and Johnson (2001, 2004) coupled an analytical solution for the unsteady temperature distribution in an infinite-slab approximation of the stem with a rigorous, thermally-induced cellular necrosis model. With the introduction of computers, others followed a theoretical modeling approach. Some of these have focused on predicting thermal response only, without regard to the effect of elevated cell temperatures on tissue survival. Rego and Rigolot (1990) solved the differential equation governing heat conduction within the stem using a Taylor-series methodology. The stem was treated as an infinite slab, assuming constant (temperature-independent), spatially uniform properties throughout. The model predicts the temperature distribution through the stem as a function of time, but no prediction

of mortality is made. Costa *et al.* (1990) followed a two-dimensional control-volume approach with temperature-dependent thermal properties, but did not account for spatial variations in moisture and its effect on energy transfer. In a similar but unpublished work, Keane[1] included a spatially varying treatment of moisture and nonlinear temperature dependence, but this model was not compared against experimental data. As part of this study Jones *et al.* (2004) approached the problem from the thermal engineering aspect, developing a one-dimensional heat conduction model in cylindrical coordinates. In contrast to earlier theoretical models, Jones accounted for temperature- and moisture-dependent thermophysical properties, and also incorporated approximate submodels for dessication, charring, pyrolysis, and spatially varying moisture distribution, none of which were included in previously reported models.

Boundary Condition

Three of the theoretical models described previously use a known surface temperature boundary condition (Costa *et al.* 1990, Rego and Rigolot 1990, Keane[1]). Model predictive accuracy was quantified by comparing the measured and predicted cambial temperatures based on an imposed temperature-time history at the exterior surface of the stem. By contrast, Steward *et al.* (1990), Potter and Andresen (2002), and Jones *et al.* (2004) specified an energy flux boundary condition rather than temperature. This is significant from a thermal modeling standpoint as incident energy flux is more readily obtained from fire behavior models than stem surface temperatures. Further, a specified heat flux input at the stem surface requires a rigorous local energy accounting within the stem for accurate predictions of the temperature history. Steward *et al.* (1990) focused on predicting the temperature-time behavior as a function of depth for mineral soil exposed to a fire. The extent of necrosis was defined by the depth of penetration of the 60°C isotherm into the plant stem. Potter and Andresen (2002) followed a two-dimensional approach to simulate the temperature variation in a tree stem due to diurnal variations in solar heating. Their model was not intended to predict temperature variations due to heating by fire, and consequently, it did not include a prediction of stem survival/mortality.

Mortality Model

Martin (1963) and Van Wagner (1973) pointed out that the basic question that must be addressed by any fire-induced tree mortality model is which trees will live or die for a given fire behavior scenario. Consequently, the heat transfer prediction must be coupled with some method for predicting cambial cell necrosis. With the exception of the work by Martin (1963), Dickinson and Johnson (2001), and the model developed as part of this study (Jones et al 2004b) the mortality predictions of others have been based on a simple 60°C mortality threshold.

FireStem: Technical Development

It is possible for a tree to survive if the cambial tissue is destroyed on only a portion of its circumference (Peterson and Arbaugh 1986, 1989, Peterson and Ryan 1986, Brown and DeByle 1987, Durcey *et al.* 1996, McHugh and Kolb 2003). But the combined effects of root, crown, and stem damage may kill a tree, even if the stem itself is not completely girdled (Ryan 2000, Dickinson and Johnson 2001, McHugh and Kolb 2003). In any case, the key point of interest in combining stem heating and cell mortality models is determining whether or not the cambium is killed. The basic assumption followed for this study, from a whole tree

[1]Keane, R.E. 1991. Plant adaptation engineering—are tree optimally protected from girdling by fire. An Environmental Biophysics Project (unpublished). March 29. USDA Forest Service, RMRS, Fire Sciences Laboratory, Missoula, MT.

mortality standpoint, was to calculate mortality for the location with the lowest level of heating implying that if it is killed then all other locations around the stem will also be killed, girdling the tree.

The heat transfer model

Tree stems have often been treated as infinite cylinders in heat conduction models. The geometry is appropriate and lends itself readily to numerical methods. In cases where little or no heat reaches the center of an infinite cylinder, the heat conduction can be approximated as being locally one-dimensional. This local one-dimensionality was verified by modeling a 10 cm stem in a two-dimensional model and comparing the radial temperature profiles with those modeled in one-dimension (for the same local boundary condition) yields nearly identical curves (Jones 2003). This local one-dimensionality is fortunate as higher-dimensional models are not only more complicated to use, but are computationally expensive.

The governing equation for one-dimensional heat conduction is:

$$[1] \qquad \rho c \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk \frac{\partial T}{\partial r} \right) + g$$

where ρ is density (kg/m^3), c is specific heat (J/kg/K), T is temperature (K), t is time (s), k is thermal conductivity (W/m/K), and g represents a volumetric heat source or sink (g is neglected in this model, although it is possible that there could be some cases in which there is a heat sink due to sap flow). The preferred energy source term or boundary condition is a time dependent heat flux at the external surface of the tree stem, a temperature boundary condition is also possible. Equation [1] is integrated over a small, finite control volume (fig. 1) and a finite time step after the manner of Patankar (1980):

$$[2] \qquad \int_{r_w}^{r_e}\int_{t}^{t+\Delta t} r\rho c \frac{\partial T}{\partial t} dt dr = \int_{r_w}^{r_e}\int_{t}^{t+\Delta t} \frac{\partial}{\partial r}\left(kr \frac{\partial T}{\partial r} \right) dr dt$$

where r_e and r_w represent radius values at the so-called east and west boundaries of the control volume, respectively, and t and $t+\Delta t$ represent the former time step and the current time step, respectively. The integration results in the following discretized equation for Equation [1]:

$$[3] \qquad a_P T_P = a_E T_E + a_W T_W + b$$

with

$$a_E = \frac{k_e r_e}{\delta r_e}$$

$$a_W = \frac{k_w r_w}{\delta r_w}$$

$$a_P = a_E + a_W + \frac{\rho c (r_e^2 - r_w^2)}{2\Delta t}$$

$$b = \frac{\rho c (r_e^2 - r_w^2)}{2\Delta t} T_P^0$$

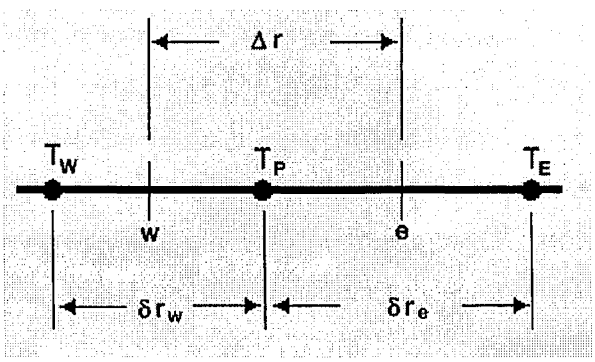

Figure 1: Schematic of a one-dimensional control volume.

where T_P is the temperature at the numerical node of interest, T_W is the temperature of the next node to the west, T_E is the temperature of the neighbor node to the east, T_P^0 is the temperature of the node of interest at the

previous time step, k_e and k_w are the conductivities at the east and west control volume walls, and δr_e and δr_w are the distances to the neighboring nodes to the east and west, respectively (fig. 1).

Equation [3] can be generated for each of n numerical nodes in the spatially discretized stem to create a system of n simultaneous equations with n unknown temperatures at each time step. The system can be solved at each time step, provided the two boundary conditions are supplied. At the centerline, symmetry prevails:

$$[4] \qquad \left(\frac{\partial T}{\partial r}\right)_{r=0} = 0$$

Equation [4] essentially forces the symmetry of one-dimensional heating. This approximation is good as long as the heating around the surface of the cylinder is spatially uniform and the grid spacing between the center most nodes is small. The boundary condition used at the surface node is:

$$[5] \qquad \left(\frac{\partial T}{\partial r}\right)_{r=r_o} = \frac{-q_P''(t)}{k}$$

where $q_P''(t)$ is the time-dependent energy flux at the surface of the tree stem, r_o is the outer radius of the stem, and k is the thermal conductivity at the surface. This boundary condition can be obtained by performing an energy balance on the outer-most control volume.

The stem heating model is capable of predicting temperatures as a function of time for discrete numerical grid points within the tree stem. For computational purposes the plant stem is divided into 600 radial cells (annular shells) aligned along the stem axis. The grid points are distributed in an exponential distribution that allocates more nodes near the cambium and bark where temperature gradients are steepest. Several grids were tested ranging from 100 nodes to 1200. The solution was unstable with coarse grids but as the number of nodes was increased the solutions converged. The 600 node grid was selected because it provided solutions similar to finer grids and it was felt that increasing the number of nodes beyond this would cause numerical truncation errors. In a similar manner it was found that a time step of 0.0625 seconds gives time step-independent solutions (Jones 2003, Jones *et al.* 2004). The analysis assumes that energy transfer through the bark plates rather than the bark fissures is the limiting factor (Kayll 1963).

Wood Properties

The primary source for the thermal properties of wood used in this study was the Wood handbook by Simpson and TenWolde (1999). Chapter 3 of the handbook contains extensive information on thermal properties of wood. For thermal conductivity the handbook gives the following:

$$[6] \qquad k = G(1.34 + 0.004064M) + 0.129$$

where G is the specific gravity based on oven dry bark and M is moisture content (%). This relation accounts for variations in species through the specific gravity. Simpson and TenWolde caution that this relation is good for wood at room temperatures, specific gravity greater than 0.3, and moisture values below 25%. While the moisture levels of the wood samples used in this study are significantly higher than this limit, no other conductivity relations exist for higher moistures. Thus Simpson and TenWolde's conductivity relation is used as a best available extrapolation. They also claim that conductivity only increases about 2% to 3% for each 10 deg C increase in temperature. Temperature rises in the hottest parts of the wood during a typical fire event are generally small (60 deg C or less). So for most fires the temperature dependence of

conductivity should have little effect. Simpson and TenWolde report that bark structure affects conductivity and it can therefore be inferred that there is some species-wise variation in wood conductivity. However, it is assumed here that this relation is sufficient for a general model, since the wood rarely experiences a large increase in temperature.

For heat capacity there is a larger dependence on both temperature and moisture. Simpson and TenWolde give the following for heat capacity of wood:

$$[7] \quad c = \frac{c_{p0} + 0.01 \cdot M \cdot c_{pw}}{1 + 0.01 \cdot M} + A_c$$

$$c_{p0} = 0.1031 + 0.003867 \cdot T$$

$$A_c = M(-0.06191 + 0.000236T - .000133M)$$

where c_{p0} is the heat capacity of oven dry wood, A_c is an adjustment for the energy in the water-wood bond, c_{pw} is the heat capacity of water, T is temperature in Kelvin, M is moisture content percent, and c is the heat capacity of the wood. This relation holds for temperatures from 7° C to 147 °C. It is likely that there is some species-wise variation in heat capacity of wood. Simpson and TenWolde do not discuss this and it is neglected in this model as well.

The density of wood is strongly dependent on species and moisture content. As the moisture content of the wood varies from the center of the tree to the bark (as shown in Martin 1963a) the following relationship was created to calculate the moisture dependent density of wood, where moisture varies with radial distance:

$$[8] \quad \rho = \rho_w \left(\frac{0.36m}{r_d} r_P + 1 + 0.27m \right)$$

where ρ_w is the density of the dry wood, r_d is the radius to the bark-wood interface, r_P is the radius at the control volume of interest, and m is the moisture percentage of the inner bark (water mass divided by dry mass). This relation approximates the densities based on the moisture profile published by Martin (1963a) and the dry wood density provided by Simpson and TenWolde.

Bark Properties

In his 1963 research, Martin provides moisture and temperature dependent relations for the thermal properties of bark (Martin 1963 a & b). For bark conductivity the following relation is given:

$$[9] \quad k = 0.042 \times \begin{bmatrix} 5.026\rho + 13.241\rho_m - \\ 0.0078(T - 273.15) - 0.397 \end{bmatrix} \times 10^{-4}$$

where ρ is the density of the dry bark (usually about 500 kg/m^3), ρ_m is the moisture density, and T is temperature in Kelvin. Martin gives bark heat capacity as:

$$[10] \quad c = 4186.8 \times (0.264 + 0.00116(T - 273.15) + M_m C_w / 4186.8 + \Delta C)$$

where c is in W/(kg K), M_m is the ratio of water mass to bark mass, T is temperature Kelvin, C_w is the heat capacity of water (in W/(kg K)), and ΔC=0.305M for M<0.27 or 0.0832 for M>0.27 (where M is moisture percent as described in the wood properties). Bark densities are

calculated for each control volume based on the same moisture profile as in Equation [8]..

Modeling Procedure

Thermal properties are assigned to each node based on the material at that node: wood, outer bark, inner bark, etc. The thermal properties are also adjusted at each node for instantaneous temperature and moisture levels. These properties are considered uniform throughout the small control volume surrounding each node of the grid. The bark thickness is calculated based on allometric equations for each species of interest. The inner most quarter of the bark was treated as inner-bark (which has a significantly higher moisture value than the rest of the bark). The bark thickness was measured at several locations on the thick plates of bark rather than in the fissures. This was considered good modeling procedure as the fissures subtend only a small fraction of the stem surface and thus if heated enough can only produce lesions at the cambium. In order for girdling of the cambium to occur, cell mortality must occur under the thick plates as well as under the

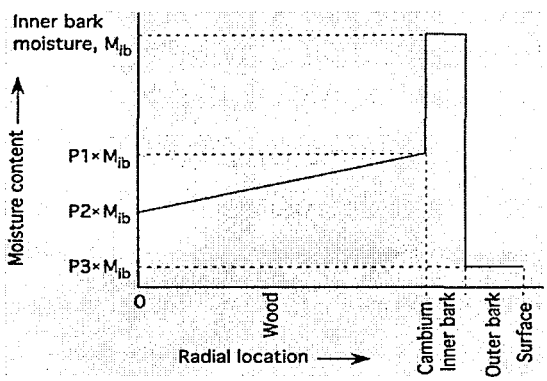

Figure 2: Moisture Profile after Martin (1963).

fissures. Thus modeling the locally one-dimensional heat transfer under the bark plates is considered the best way to obtain meaningful tree mortality predictions.

Moisture is varied in three discrete locations: wood, inner bark, and outer bark according to experimental moisture levels and in accordance to previously published moisture profiles (fig. 2; Martin 1963a). The simple experiments conducted to verify the moisture profiles consisted of sectioning and weighing samples from the three locations, drying them in an oven, and weighing them again. The experiments resulted in moisture profiles very similar to that shown in Figure 2. Moisture level affects the thermal properties, but its major impact is its ability to absorb heat as it evaporates. This evaporation of water within the bark effectively provides a protective barrier against temperature increases that can damage the stem. In the model this effect is treated on a control volume basis. The model waits until the outermost control volume with moisture still present reaches the saturation temperature, which is a function of the local atmospheric pressure. After this, it simulates the constant temperature phase change by imposing an infinite value of specific heat. The net energy into the control volume is accumulated over time until the latent heat of vaporization of the entire water mass in the control volume has been met. The control volume is thereafter considered to be completely desiccated and further heat absorption results in a temperature rise. As a fire progresses a desiccation front moves deeper into the bark. In this way it is possible to simulate the temperatures in the stem as it is desiccated without actually modeling the radial mass diffusion of water.

The evaporation of volatile materials is simulated in a similar manner. In real tree bark, different devolatilization processes occur at different temperatures with different associated latent heats, but at best there is only a limited understanding of these numerous reactions (Tillman 1981). It is therefore impractical to attempt to model all of these various reactions precisely. In this study, the devolatilization reactions are all modeled as two distinct reactions, the first taking place at 200°C. This is the temperature shown to be the

onset for devolatilization of Douglas-Fir stems (Susott 1982). The latent heat for this reaction is assumed to be equal to that of water at 200°C. It is difficult to determine the exact value for the latent heat of these phase changes, but a parametric study was conducted which varied the latent heat value up two orders of magnitude and down two orders of magnitude. The difference in predicted peak cambial temperatures for this parameter study was less than 0.1 deg C, so the latent heat of water was retained. Modeling in this manner creates a devolatilization front that penetrates into the bark just behind the desiccation front. Control volumes behind the devolatilization front are considered completely pyrolized.

This model approximates the overall devolatilization process with two separate reactions: the initial charring process at 200°C described above, and another constant temperature reaction at 600°C. These two reactions coincide with the temperature range measured for the devolatilization process in Douglas-Fir stems (Susott 1982). The reaction at 600°C is modeled in a similar manner to the 200°C reaction except that no heating above 600°C is allowed. The 600°C reaction thus serves as a temperature limit for the system. This corresponds to peak observed surface temperatures for trees in fires.

It can be readily observed that for some species (for example Douglas-Fir) the bark swells just before charring (Butler et al. 2004). This phenomenon is a strong function of species. For the Douglas-Fir in this study, bark swelling is significant. For some species bark swelling is very minimal. This phenomenon is accounted for in the model by increasing the control volume size for devolatilized control volumes by a species dependent factor. Bark swelling serves as another mechanism, in addition to vaporization of moisture and devolatilization, that attenuates heat flow into the vital tissues.

Although only a thin portion of the original bark chars, the thermal properties of the charred control volumes affect the rate of energy transfer into the vital tissues of tree stems. Due to the lack of thermal properties for charred bark, the following approximations were used in the attempt to model the heat flow through the char. For thermal conductivity a value of $k=0.05$ W/m^{2}K is used and for heat capacity $c=840$ J/kg K is used. These are tabulated values for charcoal. It has been shown that about 73% of bark is volatile material (Tillman *et al.* 1981). Therefore, the densities for charred control volumes are approximated by multiplying their desiccated mass values by 0.27 (the fraction of non-volatile material) and dividing by their current volumes. This combination of thermal properties and bark expansion is an approximation based on observation and extrapolation that matches the real measured behavior well.

Finally, when the measured surface flux was a negative value (as is the case after the fire had passed and the energy in the stem was released as it cooled to ambient temperature) it was modeled at a value of zero. This is a reasonable approximation because as the stem begins to cool energy is trapped inside by the charred layer. The char is a highly porous material and thus an excellent insulator. It acts as a nearly adiabatic layer causing heat from the warm tissues to dissipate into the cool center of the tree rather than out the surface.

Tissue Necrosis

Initially, we intended to use the mortality model proposed by Martin (1965). However, serendipitously, Matthew Dickinson a researcher in the USDA Northeastern Research Station, contacted us about a study he had been leading to develop an advanced model for tissue necrosis. Recognizing that our strengths lay in thermal modeling and that Dr. Dickinson's strengths lay in necrosis modeling, it seemed to be a perfect match to link our thermal model with Dickinson's necrosis model.

As summarized previously, the traditional approach to tissue mortality modeling has been to define a temperature between 55°C and 60°C as the lethal temperature limit above which necrosis occurs instantaneously (Van Wagner 1973, Peterson and Ryan 1986, Brown and DeByle 1987, Stewart *et al.* 1990, Gutsell and Johnson 1996). The lethal temperature concept is based on data showing that physiologically active plant tissues can survive only short exposure time to temperatures of around 60°C (Nelson 1952, Hare 1961, Kayll 1963). While the lethal temperature concept may give a rough estimate for predicting tree mortality, it has been observed that the process of thermally-induced tissue necrosis is rate-dependent, and is governed both by the temperature and duration of exposure (Hare 1961, Kayll 1963, Martin 1965, Rosenburg *et al.* 1971, Van Wagner 1973, Johnson 1974, Dewey *et al.* 1977, Levitt 1980, Gould 1989, Dickinson and Johnson 2001, Jones *et al.* 2004, Dickinson and Johnson 2004).

Tissues subjected to extremely high temperatures for an infinitesimal duration can survive. Conversely, tissues subjected to more mild temperatures can be killed if the heat is of sufficient duration. Further, the tissues of different species may vary in their ability to tolerate elevated temperatures (Lorenz 1939, Dickinson and Johnson 2004). Shirley (1936), Lorenz (1939), and later Martin (1963) recognized the shortcomings of a simple lethal temperature approach and the importance of identifying the relationship between temperature history and cambial cell necrosis. Martin (1963) proposed a method for predicting tissue necrosis based on the earlier work of Silen (1960) that cumulatively accounted for thermal injury to the cambium, thereby including the effect of both long-term, low-temperature heating and/or short-term, high-temperature heating. Silen's model included data only from Douglas-fir (*Pseudotsuga menziesii*). While the coupling of thermal transport models and the cell necrosis models was proposed by Martin (1963), such a coupled model was not developed until this study where Martins model and that proposed by Dickinson and *et al.* (2004) are included in the ***FireStem*** model.

Unlike previous models, the tissue impairment model formulated by Dickinson *et al.* (2004) and incorporated in ***FireStem*** is consistent with a large body of theory and data on thermal tolerance of both plant and animal tissues (Johnson *et al.* 1974, Levitt 1980). In ***FireStem*** thermally-induced tissue impairment is modeled explicitly as tissues are heated in contrast to previous models based on empirical descriptions of time-to-necrosis at a range of fixed temperatures (Martin *et al.* 1969, Mercer *et al.* 1994, Mercer and Weber 2001).

Dickinson et al. (2004) describe the mortality of tissues as a rate equation which models the rate of decline in tissue viability (*i.e.*, tissue impairment) as being proportional to current viability

$$[11]\quad \frac{dV}{dt} = -\kappa V(t)$$

where V is viability (-), t is time (s), and κ is a species-specific rate parameter (s^{-1}). The rate parameter κ is a function of temperature. Since tissue temperature varies with time as trees are heated in fires, the rate parameter is thus time-dependent. The parameter is modeled as an Arrhenius relation

$$[12]\quad \kappa(t) = A\exp[-E/RT(t)]$$

where A is the pre-exponential factor (s^{-1}), E is the activation energy ($J\text{-}mol^{-1}$), R is the universal gas constant (8.31 $J\text{-}mol^{-1}\text{-}K^{-1}$), and $T(t)$ (K) is the temperature at time t. Thus, the viability V is a function of time and temperature through $T(t)$. The parameters A and E are species-specific, and must be determined in laboratory experiments. These parameters have been measured experimentally for the species for which the combined model

has been evaluated here, and are summarized in Jones *et al.* (2004b). Given a living cell temperature as a function of time, a prediction of cell mortality can be made by integrating Eq. [11] with respect to time.

As tissue is heated, it loses viability over time. Initially, the (living) tissue's viability is assigned a value $V = 1$. Viability drops due to thermal damage, approaching $V = 0$ as heating progresses. It is assumed arbitrarily that tissue necrosis will occur when viability drops below $V = 0.5$. Model predictions (Jones 2003) and prior experimental data (Dickinson and Johnson 2004) reveal that under intense heating conditions typical of wildland fires, the decrease in tissue viability is rather rapid, such that the decrease in local viability V from 1 to 0 is quite sudden. Thus, the prediction of mortality is not terribly sensitive to this arbitrary criterion defining necrosis at $V = 0.5$.

At each time step in the stem heating model, the viability at each of the 600 grid points is recalculated according to Eq. [11]. As the fire heats the stem, tissue necrosis occurs near the surface, with a thermal damage front penetrating radial locations deeper within the stem over time. Thus, the result of the combined stem heating and tissue necrosis models is a prediction of which of the live cells have been killed, and which have survived. The cells nearest the surface are always the first to be damaged by fire, as they reach the highest temperatures most quickly. Tissue damage proceeds inward through the bark and, if the heating is of sufficient magnitude and duration, reaches the cambium. The distance from the bark surface inward to the deepest grid cell with viability less than $V = 0.5$ is thus defined as the kill depth.

Experimental Methods and Results

The preceding discussion described the history of stem mortality modeling and the technical aspects of the ***FireStem*** model. The following section outlines the experimental procedures and results that were used to obtain data needed to develop and evaluate ***FireStem.***

Many aspects of this study required understanding and data that simply did not exist in the open literature, this required the development of new experimental methods and techniques. These techniques and data sets are unique and experimentally quantify the heat transfer process. These data and techniques have been documented elsewhere (Jones 2003, Jones *et al.* 2004a-b, Butler *et al.* 2004). In the following we summarize the experimental methods and results.

Moisture Profile Measurements

Bark thickness and moisture distribution through the stem are critical parameters in the energy transfer process (Martin 1963a, Jones *et al.* 2004). The moisture is important because desiccation proves to be a very effective energy absorption mechanism that protects the living tissues from elevated temperatures. Accurate predictions of the energy transfer and the resulting temperature-time history in a plant stem required species-specific information about the moisture distribution. The moisture content was determined experimentally by sectioning the bark into inner (live) and outer (dead) regions, and making careful weight measurements on the bark samples before and after drying. The bark moistures were determined on a dry mass basis. The general shape of the moisture profile employed in the stem heating model was adapted from that published by Martin (1963a) (fig. 2). Martin proposed a generic moisture profile for both hardwoods and softwoods.

All parameters are referenced to the moisture content at the inner bark, M_{ib}, defined as the ratio of the moisture mass to dry bark mass. The parameters *P1* through *P3* are used to model Martin's moisture profile, and reflect the fraction of inner bark moisture content, M_{ib}, at the cambium, stem center, and outer bark, respectively. One additional geometric

parameter, *P4*, is the ratio of total bark thickness to inner bark thickness. Table 1 lists the values of these parameters for each of the species investigated here. These average values were determined both from observations and experiments. It may be pointed out that for Chestnut oak, the moisture inside the cambial layer (sapwood) was higher than the live bark, as reflected in the value of *P1* greater than unity. Given the moisture of the inner bark, the stem radius, and the total bark thickness, Table 1 was used with the general moisture profile of Fig. 2 to determine the radial profile of moisture content for all species investigated.

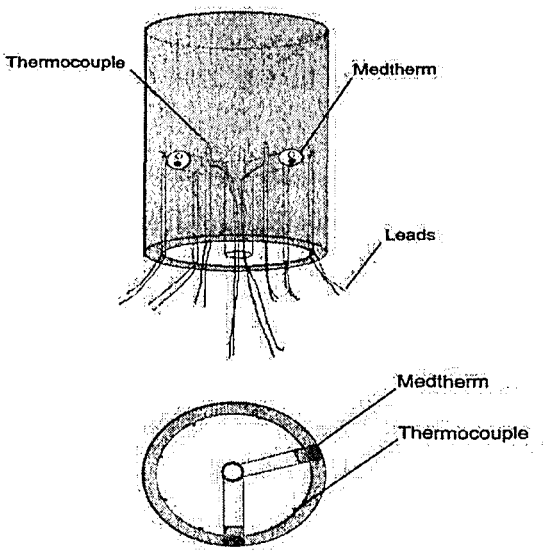

Figure 3 Schematic of experimental layout.

Analysis of the results from the experiments and model suggested that the moisture profile used for most of the experiments (*i.e.*, mature trees) was not appropriate for the smaller diameter, juvenile trees. Measurements indicated that the moisture distribution in trees of nominal diameter less than 5.5 cm was relatively uniform from the center to the surface. The moisture profile used for these small, juvenile trees was modified accordingly (*i.e.*, uniform moisture was used from the center to the surface, with the exception of a very thin layer near the bark surface, which was treated as outer bark moisture).

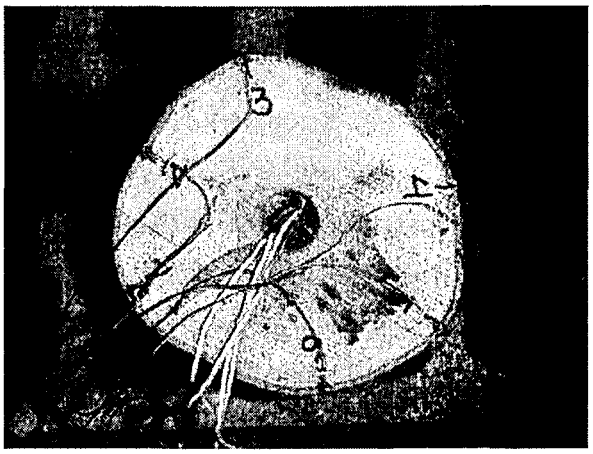

Figure 4 Photograph of topview of stem sample instrumented for testing.

Table 1. Moisture profile parameters for species tested.

	Red Maple	Chestnut Oak	Ponderosa Pine	Douglas-fir
P1	0.99	1.5	0.63	0.50
P2	0.5	0.2	0.26	0.17
P3	0.2	0.2	0.19	0.07
P4	1.5	2.9	6.0	4.0

Heat Transfer Experiments

Experiments were conducted both in the laboratory and in field settings. Researchers were able to take advantage of collaborative efforts in the Northeastern Research Station and obtain needed data from field experiments conducted in Ohio. In the laboratory experiments sections of freshly cut samples were instrumented while in the field experiments, standing trees were instrumented. In both settings the general procedures were similar (figs. 3 and 4). The laboratory

experiments were conducted at the USDA Forest Service Research Laboratory in Missoula, Montana. Field experiments were conducted in Western Montana, Ohio, Florida, Idaho, and Northern Canada. Generally measurements consisted of stem physiological parameters (i.e. species, diameter, bark thickness), incident heat flux at the exterior surface and temperatures at or near the cambium.

In most cases samples were instrumented with two heat flux sensors at the surface and either two or six thermocouples under the bark. The calibrated Schmidt-Boelter type heat flux sensors were used to measure heat flux at the surface of the test specimens. One or two holes of 2.5 cm diameter were drilled diametrically through the stem normal to the bark surface for mounting the heat flux sensors in two separate locations (fig. 3). The sensor were inserted through the holes and mounted, so that the sensing surface faced outward so as to measure the total (radiative and convective) heat flux incident on the tree stem. The leads for the heat flux sensors ran down a hole drilled within the interior of the wood and were connected to Campbell data loggers along with the leads from the thermocouples. The diameter of the stem sample sections was sufficiently large that this center hole had a negligible effect on the temperature measurements at the cambium. Figures 3 and 4 illustrate the arrangement of the instruments (laboratory setting).

Temperatures were measured using thermocouples. Initially only two thermocouples were used under the bark surface. In subsequent experiments six thermocouples were placed in an even distribution around the sample to observe the variation in the heating around the sample. In order to place the thermocouples as near the cambium as possible 0.32 cm diameter holes were drilled roughly 15 cm deep straight down the interface between the bark and wood, parallel to the stem axis. The 0.13 mm diameter Type K thermocouples were sheathed in 0.32 cm diameter ceramic sheaths and inserted into the drilled holes. Insofar as possible, the thermocouples were positioned at the vascular cambium under thick plates of the bark. More precise thermocouple placement location was determined by dissecting the bark after the burn was conducted. The thermocouples were inserted so as to lie along isotherms and disturb the heat flow as little as possible.

Bark thickness is a critical parameter for the model. Bark thicknesses and moisture content were measured for bark samples taken from the test specimens before the burns. The bark moistures were calculated on a dry mass basis, dividing the mass after oven drying by the mass before drying.

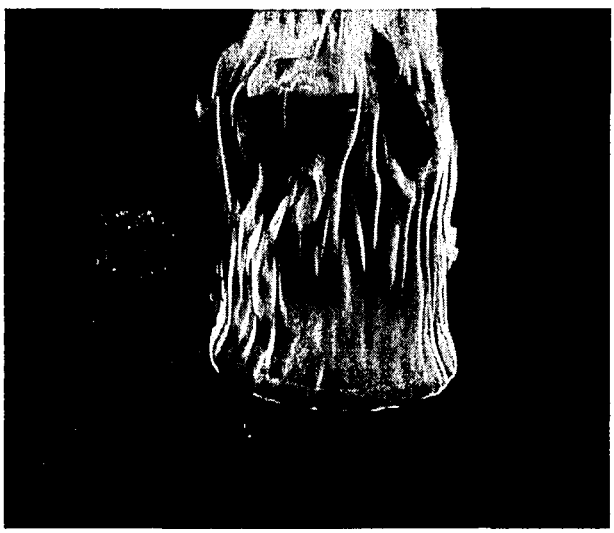

Figure 5 Photograph of stem sample undergoing heating from kerosene soaked rope.

The heat source for these experiments was generated by soaking cotton rope in kerosene, affixing the rope to the base of the stem, and igniting the kerosene soaked rope (Russell and Dawson 1995). A single or double circumference length of fuel-oil soaked cotton rope was coiled around the sample nominally 8 cm below the heat flux sensor. The rope was attached using nails (fig. 5). After ignition, the

rope was allowed to burn for 10 – 12 minutes, with peak heat fluxes typically of magnitude 30 – 35 kW/m^2. Heat flux and cambial temperature histories were measured at 1-second intervals using a data logger. The method resulted in the fire being fairly evenly distributed around the entire sample. The measured heat fluxes had a magnitude similar to measurements obtained in actual prescribed burns (Hengst and Dawson 1994). For some of the field experiments the heating source was either prescribed fire or fire generated from a fuel bed consisting of leaves, straw, poplar excelsior, corn stalks, wooden cribbing or a combination of these. When possible field experimental conditions were deliberately varied to produce a range of heating regimes, and the resulting peak total (convective plus radiative) heat fluxes were between 19 and 93 kW/m^2. In general, peak fluxes for packed leaf fuel beds were in the range 19 – 30 kW/m^2, while burns involving straw, word, and/or excelsior fuel beds produced peak total fluxes in the 35 – 90 kW/m^2 range.

Uncertainty in the measurements comes from several sources. The heat fluxes and cambial temperatures could not be measured in the same circumferential location. As there is some significant degree of variation in the flame intensity around the stem sample, it is impossible to actually obtain heat flux data that corresponds precisely with an underlying cambial temperature. The bark thickness is also highly variable. Even with the thermocouples placed under the thicker plates of bark, there is at least 1 mm of uncertainty in measuring the actual depth of the thermocouple after the fire (due to bark swelling and difficulty in dissecting the charred bark). This causes uncertainty in the measurements because the heat transfer to the cambium is highly dependent on bark thickness. Parametric model predictions reveal that a 1.0 mm error in bark thickness measurement caused approximately 3 deg C difference in peak cambial temperature. The least count (smallest increment) of the heat flux measurements were approximately 530 W/m^2.

This causes a potential error of approximately 1 deg C in peak cambial temperature predictions. A comparison of the sensitivity of the predicted cambial temperature to variations in thermophysical parameters is shown in figure 6. The comparison indicates the model is most sensitive to bark thermal conductivity, moisture content and the devolatilization parameters. Bark and wood densities and specific heat moderately affect predicted cambial temperatures.

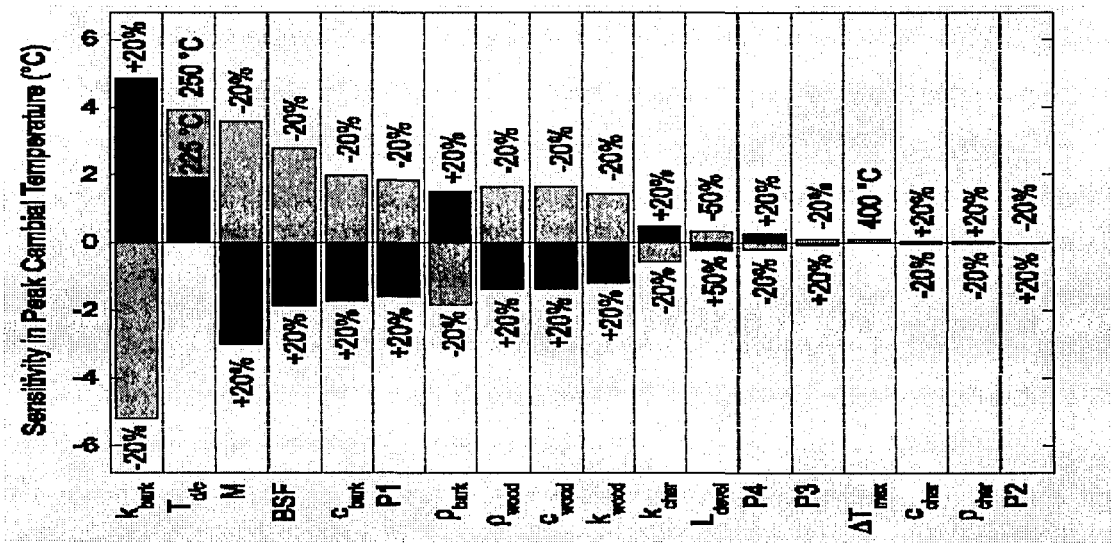

Figure 6 Model sensitivity to input parameters. k_{bark} is bark thermal conductivity, $T_{d/c}$ and L_{devol} are the temperature and latent heat of devolatilization, ρ is densities of stem components.

Validation of heat transfer model

The results shown in figure 7 give good confidence in the model's ability to predict temperatures inside tree stems when exposed to a given flux-time condition at the boundary. The modeled temperatures are in phase with the data (i.e. predicted maximum temperature occurs at nearly the same time as that observed experimentally), and their peak temperatures are both within 2 °C of the average measured peak temperature.

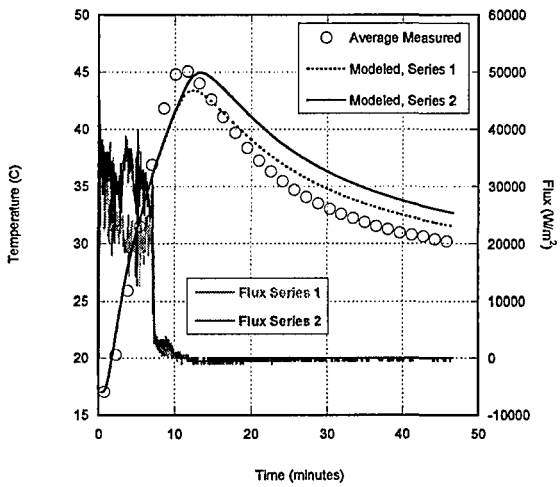

Figure 7 Modeled and measured temperature-time curves under the bark for experiment 1, as well as the heat flux measurements used in modeling these curves.

Evaluation of Combined Thermal and Mortality Model Accuracy

The approach for quantifying the accuracy of the model varied from that followed by others who compared measured and predicted cambial temperature histories (Costa *et al.* 1990, Rego and Rigolot 1990, Jones *et al.* 2004). Two indicators of model accuracy were explored: comparison between measured and predicted depth-of-kill and predicted mortality. Comparisons were made for red maple (*Acer rubrum*), and chestnut oak (*Quercus prinus*).

The depth-of-kill was determined post-mortem using a chemical stain technique (Kayll 1963). This technique was determined to be unreliable for ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*), and therefore, a modified approach was developed to assess the accuracy of the coupled model predictions for these species. For the second method of model evaluation, the model's capability to accurately predict whether or not the cambial tissue is killed was compared. The results of the comparisons are presented and their implications are discussed.

Thermal response of tree stems subject to heating was characterized by measuring the timewise variation of both the incident heat flux at the exterior surface and the temperature at the cambium. The heating source was fire, usually produced by the presence of combustible fuels manually placed around the stem. As described previously, either sections of freshly cut stems or live-standing trees were instrumented with heat flux sensors at the stem surface and thermocouples under the bark. Instrumentation for both the laboratory tests, and the field tests was similar.

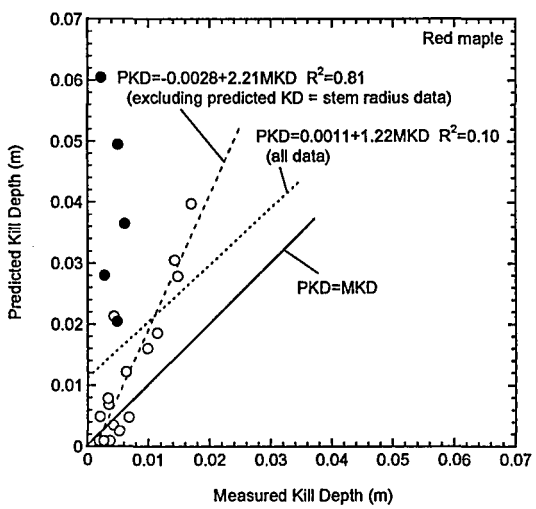

Figure 8 Comparison between predicted and measured kill depth for Red maple.

For experiments involving Chestnut oak and Red Maple, a tetrazolium trichloride (TTC) staining procedure was employed to determine the radial penetration of thermally-induced tissue necrosis, hereafter termed depth-of-kill (or kill depth). Live (respiring) plant tissues incubated in a TTC solution for approximately 18 hours turn a deep pink color as the TTC is chemically reduced to formazan (Kayll 1963). Tissues that are not respiring remain unstained. Depth-of-kill within the fire-exposed stem is

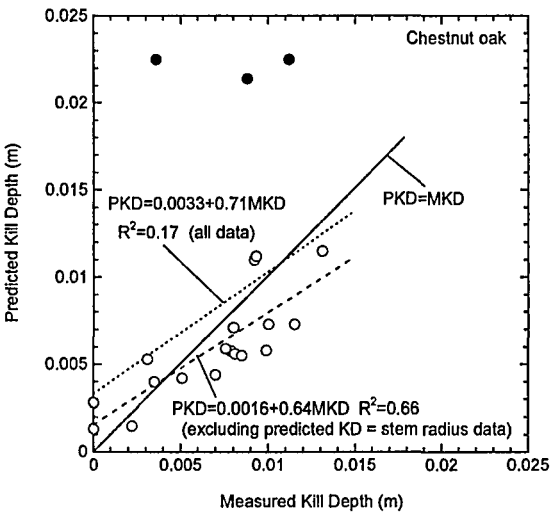

Figure 9 Comparison between predicted and measured kill depth for Chestnut oak.

thus indicated by the interface between pink and unstained tissue. For the validation of the model, the depth-of-kill was measured from the surface of the stem (bark surface) to the transition between stained and unstained tissue in thin (~4 mm thick) cross-sections of heated tree stems. The cross-sections were prepared with an electrical saw. Either two or three measurements of depth-of-kill were made at heights of 10 cm and 20 cm above the soil surface (above and below the heat flux sensor) following the chestnut oak and red maple plot burn experiments. The two or three depth-of-kill measurements from each height were then averaged. Bark thickness measurements were made at the same locations as the depth-of-kill TTC stain measurements, with an estimated uncertainty of ±0.5 mm. This method represents a direct approach to measuring tissue necrosis. Depth-of-kill thus determined was used to evaluate the model predictions for red maple and chestnut oak.

The results are presented in figures 8 and 9. Perfect accuracy in model predictions would be reflected by the predicted kill depth (PKD) matching the measured kill depth (MKD) (*e.g.*, PKD = MKD line). Included in the figure are two linear regressions. The first regression includes all predicted/measured kill depth data. The second regression excludes the data for which predicted kill depth reached the stem centerline, which are shown in filled symbols. Agreement between model prediction and these data may be compromised by one or more of the following: *i*) Initial temperatures measured by a single thermocouple near stem surface for two of these cases were abnormally high (≥ 30°C) possibly due to the stem being exposed to solar irradiation prior to the test burns. The temperatures throughout each stem were initialized with this single measured temperature, which was probably not representative of initial temperatures on the stem interior. *ii*) In the case of the Red Maple some of the outlier data were for small (juvenile) stems, with bark thicknesses of 2 mm or less. As reported by Jones *et al.* (2004), juvenile stems exhibit different moisture profiles than mature stems, and this is more difficult to generalize. Further, the bark for such juvenile stems is much thinner than for more mature stems (< 2 mm). Thus, errors made in characterizing the bark thickness and its moisture content (which represents the primary resistance to penetration of heat to the cambium) in thin-bark stems may result in large errors in predicted depth-of-kill. *iii*) As will be demonstrated in a later section, the $V = 0.5$ criterion defining depth-of-kill may or may not be appropriate, particularly for smaller stems where the temperature rises more uniformly under heating conditions. Both

linear exhibit zero-intercept with reasonable accuracy. However, the slope for the regression should be unity. The data and linear regressions reveal that, in general, the model over-predicts depth-of-kill (as seen by slope greater than unity) for the red maple, particularly at higher depth-of-kills. As was reported previously, the stem heat transfer model is quite sensitive to a number of model inputs, with bark thermal conductivity, and moisture content exercising a particularly strong influence on the predicted thermal transport (Jones *et al.* 2004). The error in predicted absolute depth-of-kill may be the result of inappropriate modeling of bark structure, uncertainty in thermophysical properties, inaccurate assumptions of initial temperature profiles, and/or assumed moisture distribution in the stem.

The TTC stain technique was not successful when applied to ponderosa pine or Douglas-fir because the staining was obscured by discoloration caused by a tissue wounding response. The technique was therefore not used to evaluate the model for these two species. Rather, an alternative approach was employed to evaluate the model. The predicted and experimentally measured cambial temperature histories can be compared to assess the accuracy of the energy transport model, as has been done previously (Jones *et al.* 2004). However, survival/mortality was determined for both experiment and coupled model prediction by integrating eq. [1] numerically subject to the experimentally measured and predicted cambial temperature histories. The result is two independent determinations of the final cambial viability, one based on measured temperature history and one based on the predicted cambial temperature history produced by the thermal model of Jones *et al.* (2004). The rate parameters for the respective species in Table 1 were used in the integration of eq. [2]. Although this is a less direct approach to determining fire-induced tissue necrosis than the staining technique, it nevertheless provides an alternate test of the accuracy of the coupled model for predicting stem survival or mortality. Comparison between predicted and measured kill depth for Ponderosa pine is shown in figure 10. A comparison between final cambial viability calculated from predicated temperature histories (PCV) and that calculated from measured cambial temperature histories (MCV). Perfect accuracy in model predictions would be reflected by the cambial viability from predicted temperatures (PCV) matching the cambial viability determined from measured temperatures (MCV) (*e.g.*, PCV = MCV line). The final cambial viability is slightly over-predicted for nearly all data. Based on our observations that for this species the model consistently underpredicted cambial temperatures we conclude that the discrepancy between predicted and measured cambial viability is due to the thermal model.

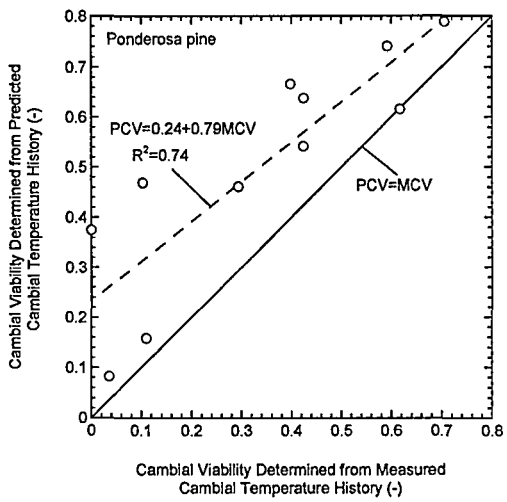

Figure 10 Measured and modeled cambial mortality for Ponderosa pine.

Jones *et al.* (2004) reported experimentally measured cambial temperatures for Douglas-fir stems exposed to heating using the rope-burn approach. Heat flux sensors were used in each experiment to characterize the incident flux during the burn, and cambial temperature histories were measured at several locations and averaged. Following the same coupled

model evaluation approach as that applied to ponderosa pine in the foregoing section, The Douglas-fir data reported by Jones *et al.* (2004) were used to explore the model's predictive accuracy for this species. Figure 11 shows the variation of average measured cambial temperatures with time (solid symbols) and predicted cambial temperatures as reported by Jones *et al.* (2004) for four different heating cases. The figure also illustrates corresponding cambial viability histories as predicted from *i*) experimentally measured cambial temperatures (open symbols), and *ii*) predicted cambial temperatures. The solid and dashed lines (for both viability and temperature) are predictions based on the two different heat flux histories measured at the stem exterior surface during the experiments. As expected cambial viability drops due to thermal damage as the temperature rises. Predictions of cambial viability based on predicted cambial temperatures (using the two different incident flux series as input) agree closely with predictions of viability determined from measured cambial temperatures in Cases (a) and (c). As expected from the temperature dependence of the tissue necrosis model, under-predictions in cambial temperature by the stem heating model in Cases (b) and (d) result in over-predictions of cambial viability. For the heating intensity and durations of these tests, cambial viability never reaches $V = 0.5$, arbitrarily defined here as the threshold for necrosis. Further work is needed to characterize how tissues respond to long-term, low-temperature heating.

The coupled model predicts absolute depth-of-kill with only marginal accuracy, but correctly predicts stem survival/mortality for approximately 75% of the cases (fig. 12). Inaccuracy in the combined models comes from three sources: uncertainty in the experimental measurement of model input data, error and approximation in the stem heating model, and error and approximation in the tissue necrosis model. Trees are composed of anisotropic, non-homogeneous materials for which physical properties are little understood. The fire that is heating the stem is almost always highly turbulent and variable in intensity. Error and/or approximation in the stem heating model have been discussed in detail by Jones *et al.* (2004). Error associated with the tissue necrosis model comes from

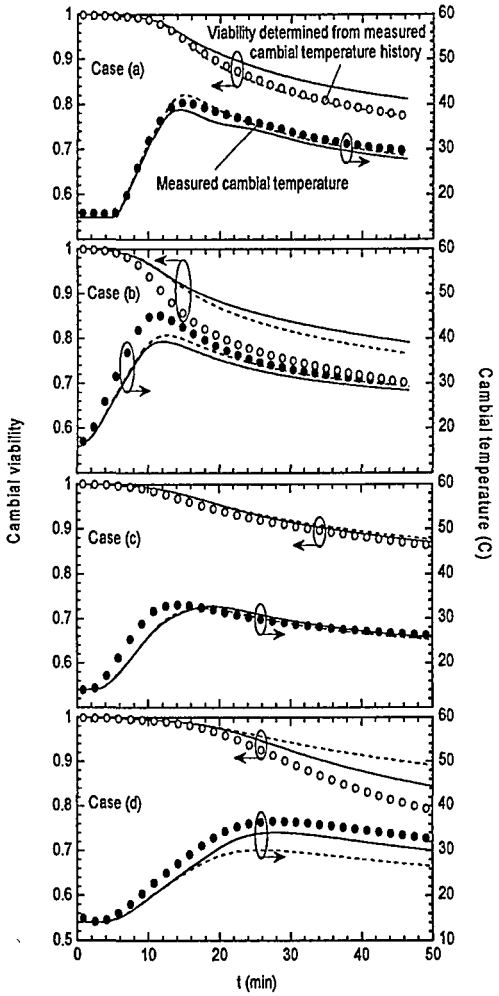

Figure 11 Measured cambial temperatures (solid symbols) and predicted cambial temperatures for Douglas-fir (*Pseudotsuga menziesii*) from Jones *et al.* (2004), and cambial viability histories as predicted from *i*) measured cambial temperature (open symbols), and *ii*) predicted cambial temperatures. The solid and dashed lines (for both viability and temperature) are predictions based on two different incident flux series measured during the experiments.predicted for approximately 75 percent of the test cases.

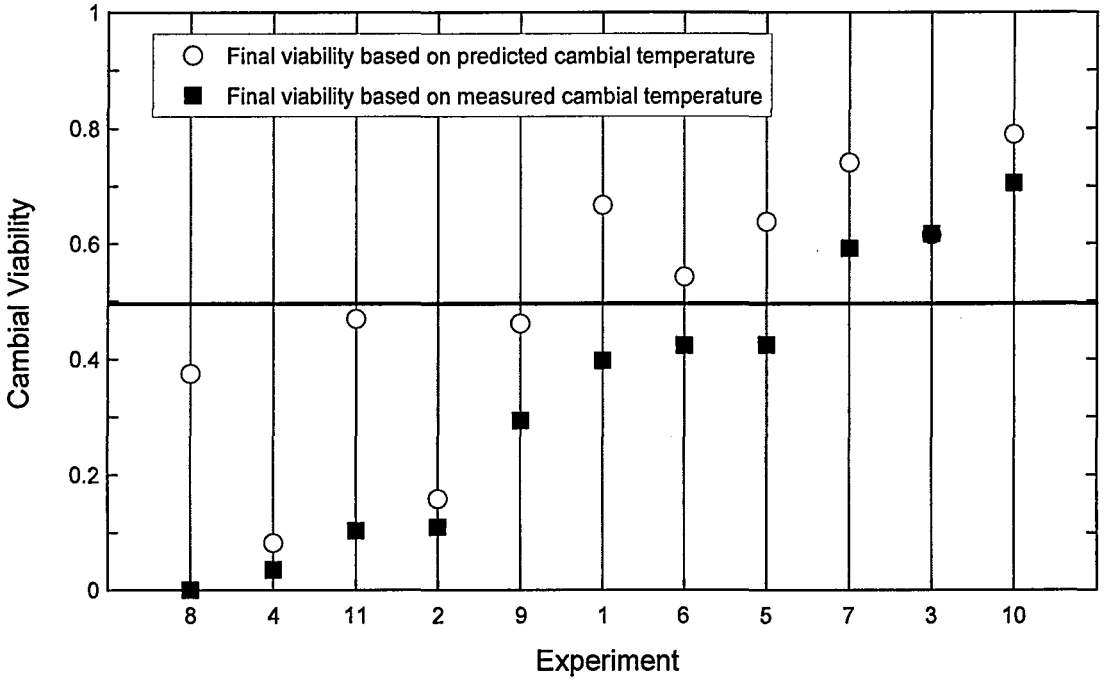

Figure 12. Predicted versus measured cambial viability for Ponderosa Pine. Note that viability is correctly predicted for 8 of the 11 cases. Similar accuracy occurred for the other 3 species.

variation from tree to tree in tolerance to elevated temperatures and the approximations in the tissue necrosis model. The errors associated with the stem heating model, tissue necrosis model, and experimental measurement can be cumulative or multiplicative. The data reveal that even with the uncertainty inherent in the process, the combined models have the ability to correctly predict cambial mortality most of the time.

Current Status and Future Direction

For this study we concentrated on four tree species selected to generally represent two hardwood and two softwood species (*Acer rubru, Quercus prinus, Pinus ponderosa and Pseudotsuga menziesii*) of interest to forest managers in North America. Results indicate that while the model predicts absolute depth-of-kill into the plant stem with only marginal accuracy, stem mortality/survival was correctly predicted for approximately 75% of the cases studied. Given the complexity of the physical processes occurring in the heating and subsequent tissue mortality we believe this is very good.

Comparison between measured and predicted temperature profiles suggests that the thermal energy transfer model captures the dominant physical processes.

Little discussion of the process of linking the ***FireStem*** model to a fire behavior model was presented. The reason is that currently used fire behavior models do not explicitly provide radiant and convective energy fluxes. They are empirical in nature and provide a measure of fire intensity through Byram's fireline intensity. Unfortunately this is not an engineering quantity. However, recognizing this fact, the ***FireStem*** model has been formulated to accept not only time/heat flux boundary conditions (so that it can be directly linked to new fire behavior models as them come available), but recent work has indicated that the transient heat flux pulse that has been measured experimentally (e.g., fig. 7) can be approximated by a "tophat" profile. This

implies that the time varying energy source can be defined by just two terms, a magnitude and duration. With this realization, ***FireStem*** was written so that the user can specify a constant fire intensity and duration using slider bars in the main ***FireStem*** window.

In its current version ***FireStem*** allows the user to specify the energy at the bark surface either by reading a data file directly or by specifying intensity (a unitless quantity-low medium and high) and duration of burning. The last manuscript in progress at this time is intended to quantify a relation between the unitless fire intensity option in ***FireStem*** with Fireline intensity which is provided by currently used fire models. This approach will allow coupling of the ***FireStem*** model with currently used fire behavior models until such time that more advanced fire models are produced and implemented.

FireStem has been tested against experimental data collected from four tree species. Extension of this tool to additional species requires that additional thermal properties be gathered and included in ***FireStem***. Some data are available from the available literature base, but much of the data will require additional laboratory measurements. Such measurements are not difficult and can be accomplished using relatively straightforward experimental techniques.

Similarly, Dickinson et al. (2004) has shown that the rate parameters governing the tissue necrosis model are species dependent. This implies that extension of the ***FireStem*** model to additional species should also include additional characterization of the parameters defining the necrosis model.

In our opinion the ultimate goal should be the development of a comprehensive system for predicting fire-induced tree mortality. This system should include models for simulating the effects of fire on the roots, stem and canopy. Based on the combined injury to the whole tree it would then predict whole tree mortality. As described earlier, one basic assumption of ***FireStem*** is that the calculation is done for the location on the tree stem that receives the lowest energy flux, therefore if it is killed all other locations around the stem are killed and the stem is thus girdled. It is possible for a tree to survive if the cambial tissue is destroyed on only a portion of its circumference (Durcey *et al.* 1996). However, a scar will form in areas where the cambium has been killed. A future version of this model could be envisioned that allows the calculation of fire scar size as a function of species, stem size and fire intensity and duration.

FireStem can form the foundation from which such as system can be constructed. Figure 13 identifies the general logic of such a system. The research team is currently in place and "up to speed" on the state of the science. It is our hope that the Joint Fire Sciences Program Governing Board will consider the option of funding a follow-on proposal to further this research effort.

Deliverables

Knowledge of fire-induced shrub and tree mortality is critical to accurate evaluations of the various fuel and land management methods available to land managers. This study proposed to develop and document a computer-based system linking a new physics-based stem heating model with duff burning and surface fire models. Below are listed the deliverables from the original proposal and our (probably biased) evaluation of how successfully we met those promised products:

(1) Produce a computer based system for prediction of fire-induced plant mortality by heating of the roots and/or bole. This will include direct links to a duff burning model and surface fire model.

FireStem represents the successful fulfillment of this promised product. Root

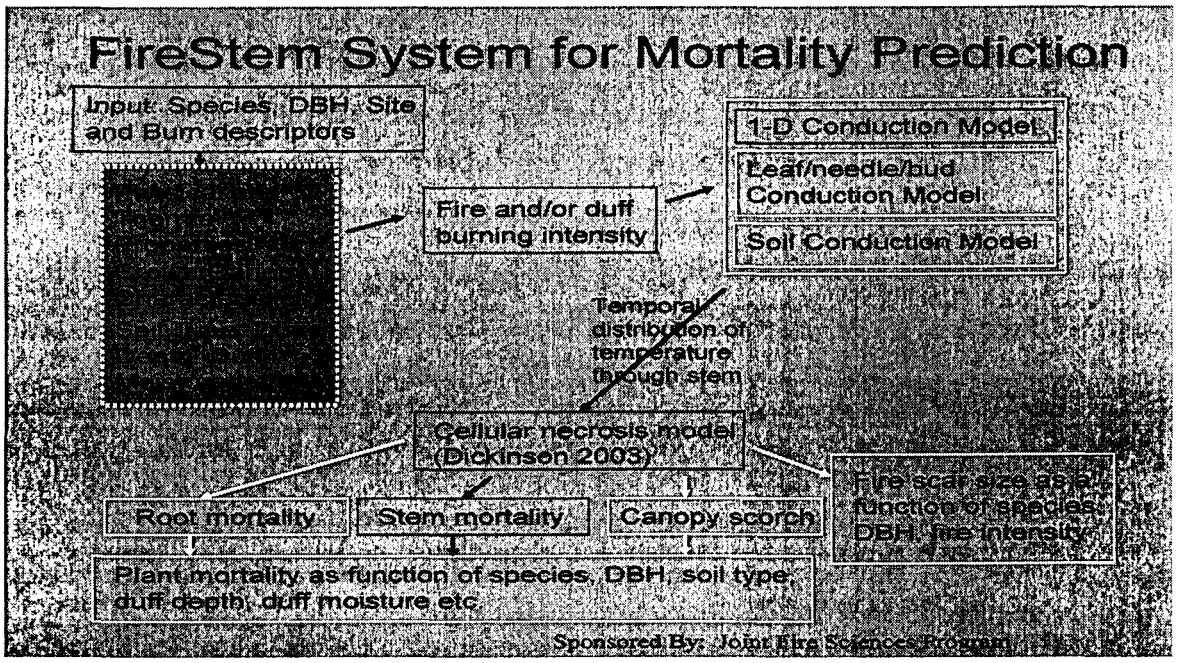
FireStem System for Mortality Prediction
Input: Species, DBH, Site and Burn descriptors
1-D Conduction Model
Leaf/needle/bud Conduction Model
Soil Conduction Model
Fire and/or duff burning intensity
Temporal distribution of temperature through stem
Cellular necrosis model (Dickinson 2003)
Fire scar size as a function of species, DBH, fire intensity
Root mortality
Stem mortality
Canopy scorch
Plant mortality as function of species, DBH, soil type, duff depth, duff moisture etc
Sponsored By: Joint Fire Sciences Program

Figure 13 Logic diagram for comprehensive tree mortality predictive tool that included fire-induced injury to roots, stem and canopy. Dark frames represent components currently developed, gray frames represent future research efforts.

heating has not been explicitly included, but ***FireStem*** was formulated to accept a root surface heat flux boundary condition. The original proposal stated that this effort would include root heating. The model was designed to be applied to any generally cylindrical plant structure (roots, stem, branches). The heat transfer model can be applied to roots but still requires either a temperature/time or energy flux/time boundary condition. Subsequent efforts in this area will focus on linking available soil heating models to the stem heating and mortality model to predict root mortality.

(2) A Users Interface that allows the user to select from preset species dependent physical parameters or input custom plant parameters. This will synthesize the current state-of-knowledge on shrub and tree mortality by fire.

FireStem has been designed with a User-friendly interface that allows the user to select from a present list of species, specify the stem diameter range of interest and the fire intensity and duration.

(3) Peer-reviewed technical papers will describe the technical details of the model and compare model performance against data from experiments and previously published data.

The scientific aspects of this study have been documented through the publication of a masters degree thesis, five presentations at conferences or technical workshops, and four peer reviewed journal publications (one currently published, two in review and one nearly ready for submission).

(4) The software, accompanying manuals, and technical papers will be contained on CD-ROM to be published by the Rocky Mountain Station.

The appendix includes a copy of the current version of the ***FireStem*** users manual. The

software, technical documentation, and users' guide are available on the world wide web at : http://www.firelab.org/fbp/fbresearch/stemheating/Homepage.htm

Conclusions

A stand-alone executable version of a model for predicting fire-induced cambial tissue mortality in a tree stem has been developed (***FireStem***). ***FireStem*** predicts species and diameter dependent mortality of the tree stem cambial tissue as a function of fire intensity and duration. The scientific aspects of this study have been documented. A website has been developed that includes technical publications, the ***FireStem*** executable computer code and a users guide to ***FireStem***

http://www.firelab.org/fbp/fbresearch/stemheating/Homepage.htm

Research has indicated that ***FireStem*** accurately predicts mortality for 75% of the test cases. Based on this success, it can form the foundation of a comprehensive tool for predicting whole tree mortality caused by the combined effects of fire-induced injury to the roots, stem and canopy of trees.

Acknowledgement

This project has been technically challenging and rewarding. The financial support of the JFSP is sincerely appreciated. It is our hope that additional funding can be secured to maintain the current momentum towards a comprehensive system for predicting fire-induced tree mortality. The willingness of Dr. Matthew Dickinson to share his research results and guide our development of the ***FireStem*** model have proved invaluable.

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FireStem.....a stem heating tree mortality model.

The following is a simple and basic users guide to ***FireStem*** a model for predicting fire-induced mortality of the cambium layer in tree stems.

Introduction: ***FireStem*** is a computer model designed to aid fire managers with predicting tree mortality based on fire behavior and intensity. The eventual goal is to link ***FireStem*** and *BahavePlus* to produce mortality predictions based on fuel loadings, moisture, and fire behavior for a given region and a range of tree species. To date, we have developed and validated ***FireStem*** for four species, Douglas Fir, Ponderosa Pine, Chestnut Oak, and Red Maple. Other species will be added as their thermophysical properties are identified and validated. ***FireStem*** is based on fundamental thermodynamics and heat transfer taking into account the thermophysical properties of individual species in order to predict temperature at the living tissue or cambium. Eventually, the user will be able to input a range of species for a given ecosystem, run ***FireStem*** and review the mortality prediction for a range of diameters for each species. Below follows step by step instructions for running such a simulation for the four test species mentioned above.

Instructions for running ***FireStem***

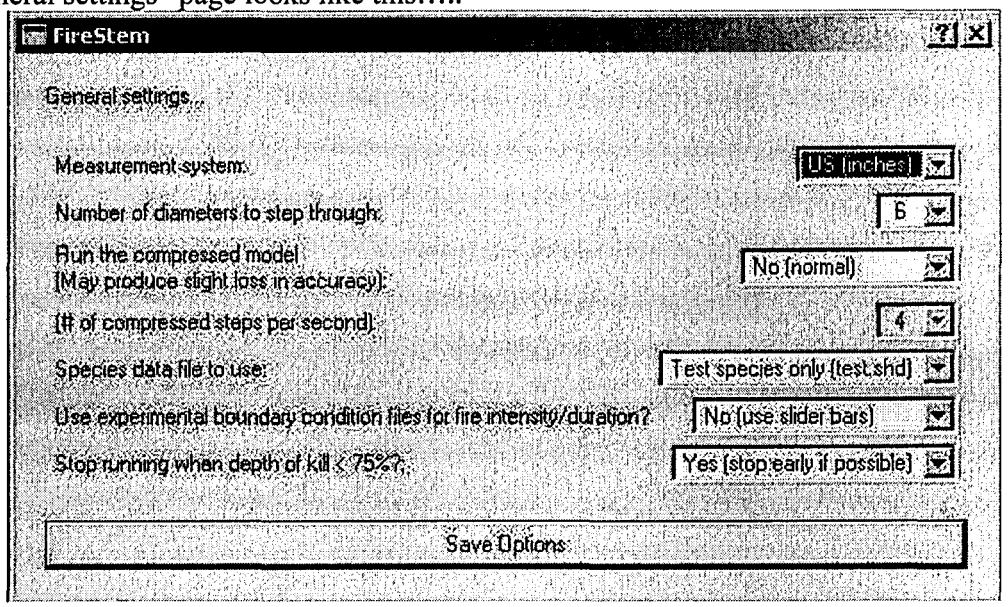
Double click on the ***FireStem***.exe icon to start the model.

Click on **"Options"**, then **"General Settings"** to view the general settings.

General settings include:
Measurement system: This gives the user the option to use either metric or US dimensions.
Number of diameters to step through: This allows the user to choose a range of up to 10 diameters to test. Note: the more diameters investigated the longer the computer takes to run a simulation. *We suggest a range between 4 and 6 initially.*
Run the compressed model: The compressed model runs faster but is less accurate due to less iterations in the model. *Depending on your computer speed, we recommend running the non-compressed version.*
(# of compressed steps per second): When running the compressed version, the user can choose from 2 to 16 steps per second. Note: the fewer the steps per second the less accurate the results, but faster the simulation. *If you run the compressed version, start with a minimum of 8 steps per minute.*
Species data file to use: The user can choose from a **"Test species"** database which contains the four main species that were used to validate the model to date, or from the **"All species"** database which contains a sample of species from differing regions. The **"All species"** database is somewhat limited at the moment but will be expanded with time.
Use experimental boundary condition files for fire intensity/duration? The experimental boundary conditions were used to validate the model. It is recommended that the user always choose the **"No (use slider bars)"** option.
Stop running when depth of kill <75%: This option allows the user to exit the model calculations once a valve for kill depth is less than 75% of the bark thickness for each size class, thus reducing the overall time to run a simulation. In other words, if the heat pulse only

penetrates the outer 75% of the bark or less for a given diameter then the model exits at that point rather than continuing due to the fact that bark thickness only increases with size. *In order to increase the computation time we recommend selecting "Yes" on this option.*

A typical "General settings" page looks like this.....



Once the user has selected the desired settings, click **"Save Options"** to return to the main page.

Click on **"Options"**, then **"Graph options"** to view the general graph settings.

Graph options simply give the user the choice between extrapolating the X and Y axis or not.

Click **"Save Options"** to return to the main page.

Click **"Run"** then **"Run 1-Dimensional model"** to view the parameter input menu.

The menu includes dropdown boxes for inputs for tree species, minimum and maximum stem diameter, percent (%) moisture of the inner bark, and bark thickness. Below follows a brief description of each.
Species: Select the species of interest from the dropdown box.
Min dia: Type in the minimum diameter size class that you would like to investigate, or use the default value. *Depending on the units selected, we recommend that users choose a minimum diameter no smaller than 2 inches or 0.05 meters.*
Max dia: Type in the maximum diameter size class that you would like to investigate, or use the default value.
Moisture (%): This value is actually the percent moisture at the inner bark or the moisture associated with the living tissue. The value varies seasonally and is not easily achievable; therefore, default are provided and it is suggested that you user experiment with the different values to observe how the results vary in order to "bracket" mortality for a give scenario.

Bark thickness: Bark thickness is well defined for most tree species and is dependent upon tree diameter. These mathematical relationships are contained within the model; however, it is recognized that there can be some variability among species depending on site productivity. The dropdown box for **"Bark thickness"** gives the user the ability to account for this variability if it is known.

Once each menu box has been completed for a species the user is then prompted to do the same for the next species of interest, up to four species.

Next, click on the **"# of steps to run:"** box and select the number of diameters to step through, from 2 to 10, for each species. This value was previously established during in the **"General settings"** option described above, but it is conveniently placed here as well to make adjustment rather than go back into the **"Options"** setup.

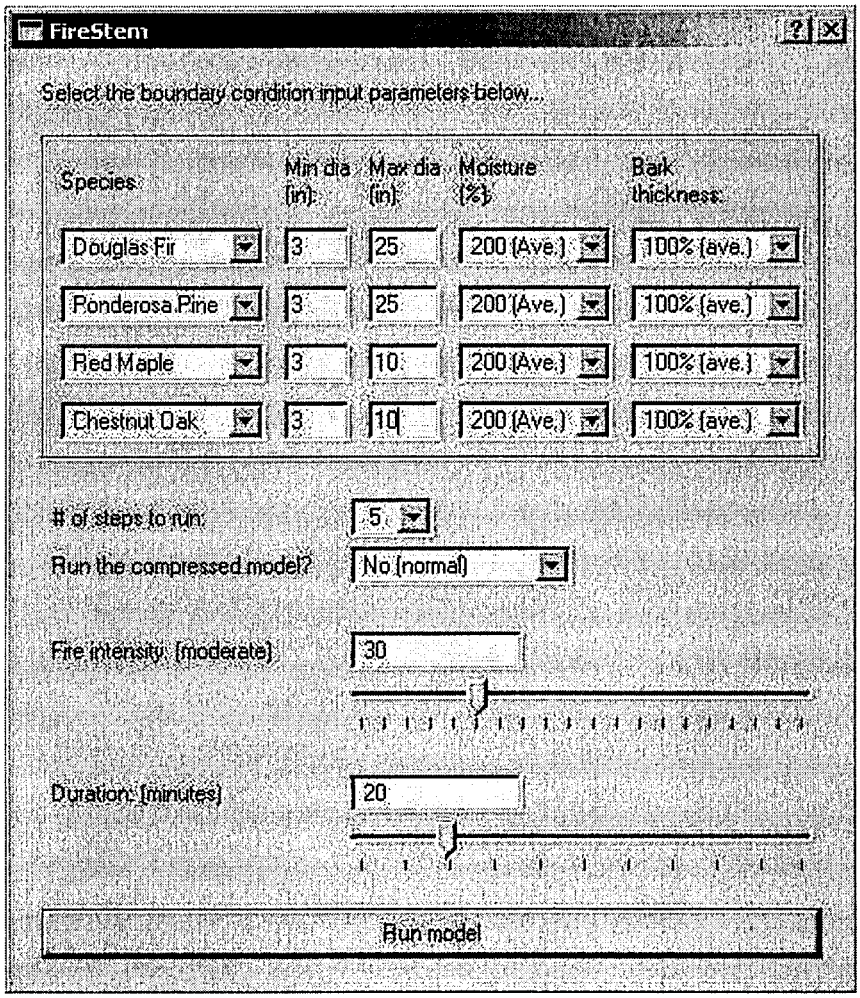
Next, the user is again given the option to run the compressed model.

The redundancy of the last two steps may become obvious after running the model for the first time. Depending on computation time, the user may wish to speed up the simulation by either evaluating fewer steps or running the compressed model.

Next, select the **"fire intensity"** by clicking on the slider bar. The value for fire intensity is energy per unit area (kW/m^2), also known as heat flux, and is recognized in this case as the amount of energy released from the fire and received by the tree stems. It is this energy that is input into ***FireStem*** and used to calculate the cambium temperature for each species at each of the specified size classes. The range of fire intensity is from 5 (very low) to 100 (very high). An example of each would be a slow moving fire in needle cast with flame lengths between 6-12 inches verses a fast moving fire in heavy fuels with flame lengths ranging from 4-10 feet respectively.

Finally, select **"Duration: (minutes)"** from the slider bar. This value is simply the length of time that each diameter size class is exposed to the above specified **"fire intensity"**.

A typical input page looks like....

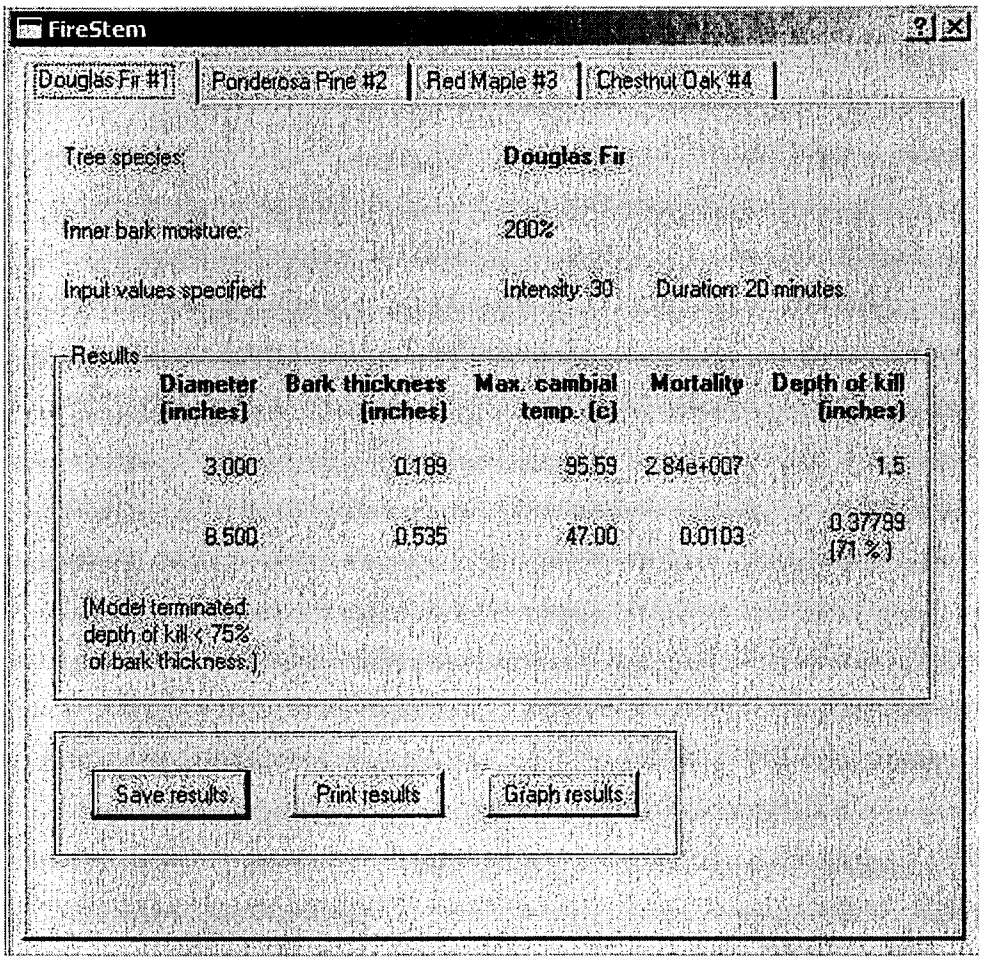


Once the setup is complete, click on **"Run model"**.

A status bar will appear and give percent (%) completion along with the option to "cancel" the simulation.

Interpreting Results

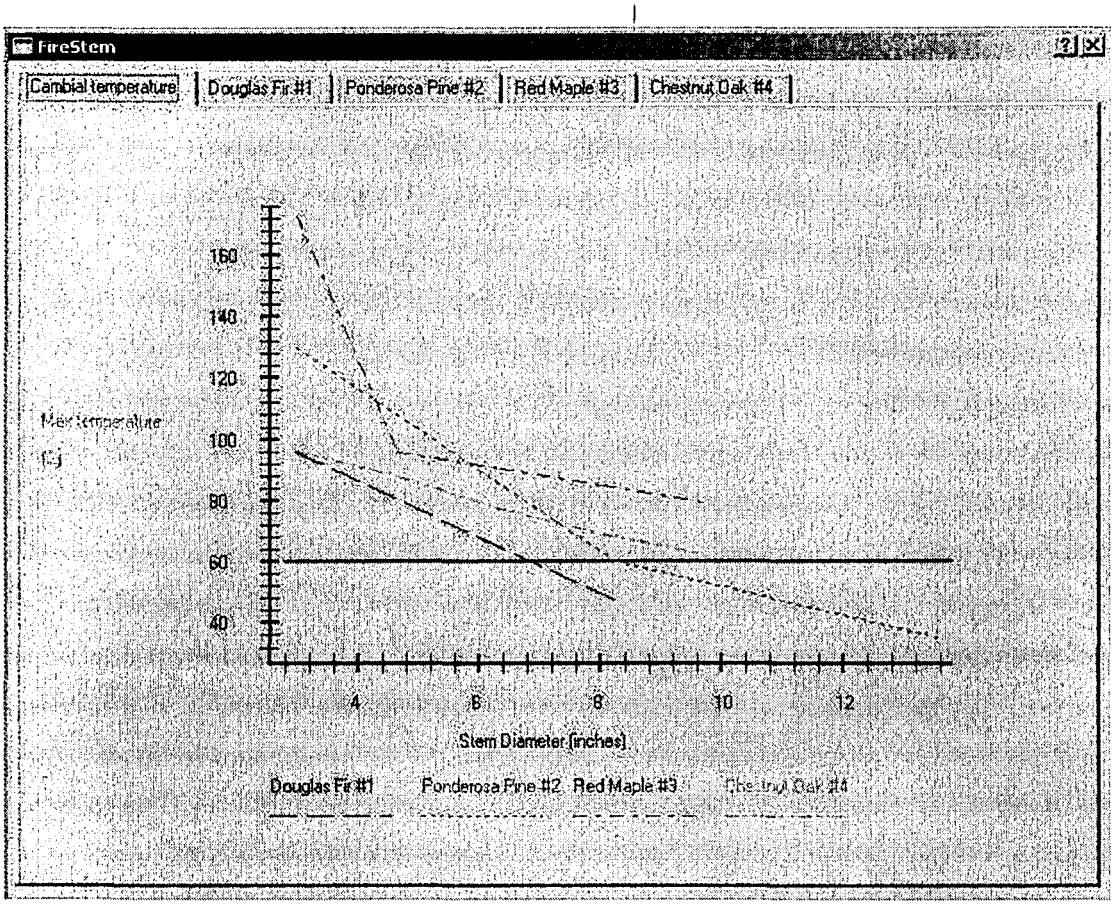
Once the simulation is complete the results will appear in tabular format. The results for the simulation outlined above are shown below.



Results are compiled for each of the species tested in the simulation, in this case Douglas Fir, Ponderosa Pine, Red Maple, and Chestnut Oak. The results for each are viewed individually in tables which include a summary of the simulation conditions as well as mortality predictions, seen in red. In the case above we see mortality predicted for the 3 inch size class and survival predicted for the 8.5 inch size class. The simulation at this point was terminated for Douglas Fir due to the fact that depth of kill was <75%, seen in the final column.

Note that this is a good start for getting an idea of the extent of mortality for Douglas Fir. The next step would be to rerun the simulation leaving all parameters the same, but changing the diameter range from 3 inches to 9 inches. The results of such a simulation would refine the large gap in the mortality prediction.

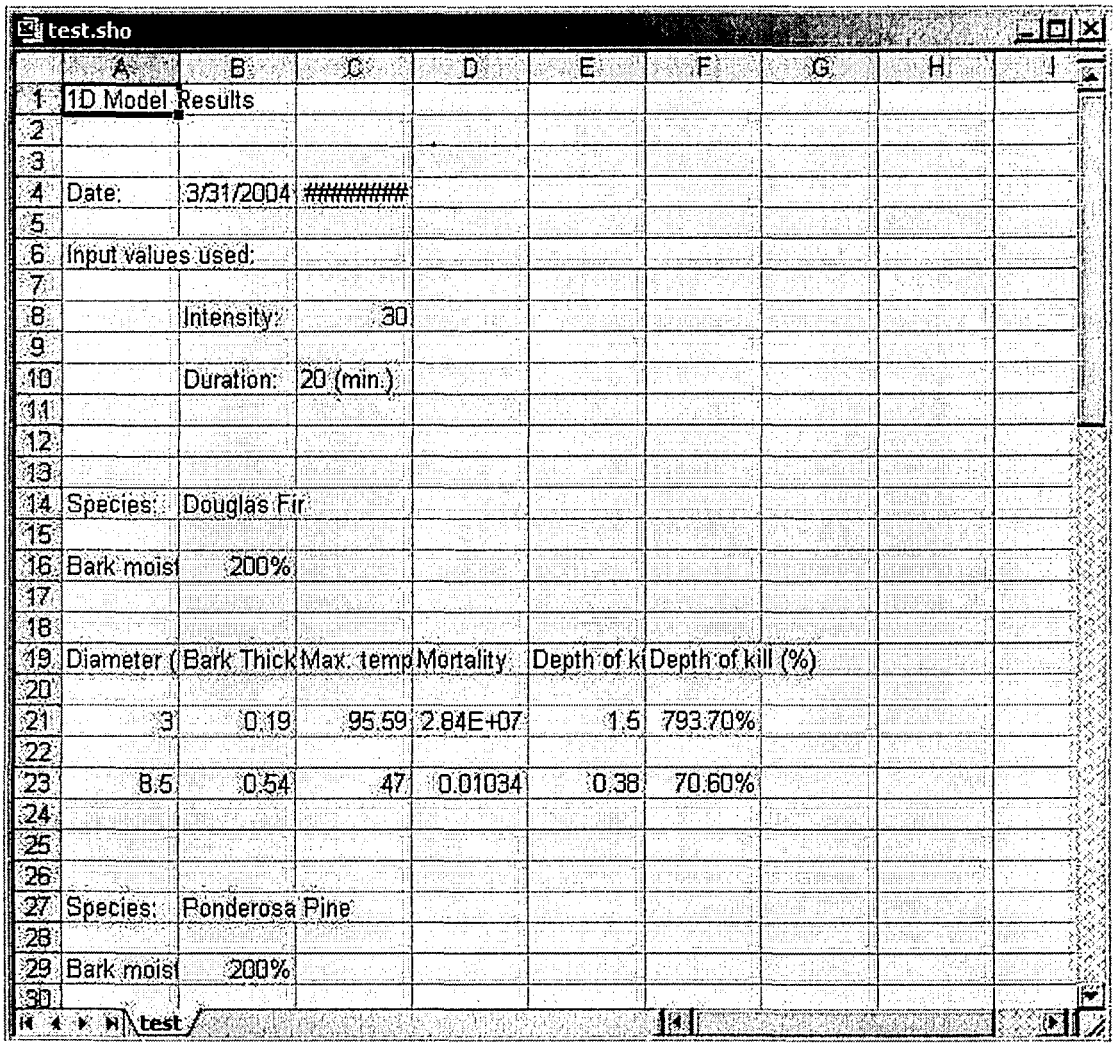
Next, click through the remaining species to view the simulation results, or click on the **"Graph results"** tab to view the graphical results of the simulation. The graphical results can be viewed for each individual species or for all the species combined, as seen below.



The graph features include **"Max temperature (C)"** along the y-axis, **"Stem Diameter (inches)"** along the x-axis, and a solid red line along the 60°C plain. This solid red line is the threshold temperature for mortality; therefore, any point above the line indicates mortality for that species at that size class.

The graphical results for the individual species contain the same information, but plot **"Depth of kill"** and **"Bark thickness"** along the y-axis verses **"Diameter"** along the x-axis.

At this point it is not possible to print the graphical results, but the simulation results can be saved and imported as a text file into a variety of software applications that have graphing options, such as Excel. In order to do this, close the graphical output page and click **"Save As"** on the results page. The file format is *.sho (stem heating output). Once the file is saved, locate it in your file manager and open it in Excel. The results for the entire simulation will be in spreadsheet format, as seen below. In the Excel spreadsheet are the results from the same example that has been outlined above.



test.sho

	A	B	C	D	E	F	G	H	I
1	1D Model Results								
2									
3									
4	Date:	3/31/2004	#########						
5									
6	Input values used:								
7									
8		Intensity:	30						
9									
10		Duration:	20 (min.)						
11									
12									
13									
14	Species:	Douglas Fir							
15									
16	Bark moist	200%							
17									
18									
19	Diameter (	Bark Thick	Max. temp	Mortality	Depth of ki	Depth of kill (%)			
20									
21	3	0.19	95.59	2.84E+07	1.5	793.70%			
22									
23	8.5	0.54	47	0.01034	0.38	70.60%			
24									
25									
26									
27	Species:	Ponderosa Pine							
28									
29	Bark moist	200%							
30									

test

This is a convenient way to save and compare several simulations. Once saved, close the results page and if you wish to run another simulation click on **"Run"** and **"Run 1-Dimensional model"** to get back into the model input page, or close the model to quit.

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